Optically Activated Switch Using High Power Laser Diode Arrays

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Summary

Because of their high PRF capability and compact size gallium arsenide laser diodes offer distinct advantages as the light source in optically activated switches. In this paper various targets were investigated using a 500 watt laser diode array as the optical source. The targets included silicon, and gallium arsenide. Switch characteristics (recovery, gap resistance, rise-time) were obtained as a function of optical energy, optical pulsewidth, and gap length. Bias voltages up to 6 kV were employed. Trade-offs in performance are discussed for the various targets. Gap resistances as low as 18 Ω were achieved for a $\approx$ 1/2 mm gap. Suggestions to further improve device performance, using laser diode arrays, are discussed.

Introduction

In recent years the optically activated switch has received increasing attention because of its potential in kilovolt pulser circuits.[1,2] Interest in the optical switch stems from several unique properties, which gives rise to important advantages in pulser technology. Among these properties is the fast switching speed. As is well known, the optical switch consists of an intrinsic semiconductor whose conductivity is rapidly increased by the application of a light pulse, creating carrier pairs in large numbers (Fig. 1). If the light intensity covers the entire semiconductor gap there is no transit time limitation and the switching action is very rapid. The switching mechanism is accompanied by low jitter, as well as a capability for high PRF operation. Another important feature is the electrical isolation of the light signal from the switch. In many pulser applications, the switch potential floats above ground and isolation circuit elements must be introduced to drive the switch (typically a thyratron or a spark gap). In the case of the optical switch there is no need for isolation elements. Finally, the optical switch has the advantage of being a bulk device. In principle, therefore, voltage and current may be increased simply by scaling up the size of the device.

Certain drawbacks of the optical switch should be mentioned. First is the relatively low current gain (approximately one photon needed to create one carrier pair). Much light energy, often produced inefficiently, is thus needed. In addition, the advantages of speed, low jitter, and high PRF capability are possible only if the light source itself satisfies the same stringent requirements. In a sense the burden of operation has been shifted from the semiconductor switch to the light source. For example, a Nd:Yag laser is often used as the light source. Although this laser satisfies the energy and speed requirements, it suffers from PRF limitations.

Recently laser diode arrays have become available with peak powers in excess of 500 W. These diodes are capable of operating at very high PRF (up to one MHz) while supplying sufficient energy to result in good switching efficiency. The laser diodes also are compact compared to many other types of light sources, a definite advantage in system applications.

In this paper both silicon and gallium arsenide targets are investigated using laser diode arrays (GaAs) as the optical source. Gap resistance and recovery measurements are presented for targets with gap lengths of 1/2 to 5 mm, and for voltages of 1 to 6 kV. Results show that efficent operation at high PRF is feasible using laser diode arrays.

Discussion

On-State Resistance

It is useful to write down and discuss the on-state resistance R for the semiconductor:

$$R = \frac{L^2 E}{P_o T_r(\mu_e+\mu_n)(1-e^{-t/T_r})} \qquad (1)$$

In this equation L is the gap length (cm), E is the photon energy (eV), and u_e and u_n the electron and hole mobilities (cm^2/V-s). Po is the constant power output from the optical source, which is switched on at time t=0. T_r is the bulk recombination time. Once the optical pulse is turned off the resistance grows as e^{t/T_r}. One should note R approaches a lower limit for times much larger than the recombination time. There is therefore a limit to the amount of light energy one can hope to accumulate and convert to carrier energy. In view of Eq. (1), one must carefully consider the relative values of optical pulsewidth and recombination time, as well as the desired gap resistance. In general, if one desires a low gap resistance for long times (exceeding T_r) then one must increase the light intensity sufficiently high to overcome the diversion of energy caused by recombination.

Eq. (1) does not take into account several significant effects, most of which tend to

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increase the gap resistance beyond that predicted by the equation given here. These effects include light reflection from the semiconductor, transmission effects, contact resistance, mobility changes, quantum efficiency, and temperature effects. In principle, light reflection may be minimized by use of an anti-reflection coating, which also serves to passivate the target. Transmission effects occur when a significant portion of the light exits from the opposite side of the semiconductor. This effect may be minimized by increasing the thickness of the semiconductor, reflecting the emerging light, or by changing the optical wavelength. Contact resistance may be reduced in magnitude by proper alloying or by using n type dopant in the electrode region. Ambipolar mobility becomes important at the higher current densities. Its effect is to reduce the overall mobility. One should also mention that the mobility is field dependent. Quantum efficiency depends on optimum matching of the optical wavelength and the gap energy for a desired thickness of the conductivity layer. In addition, the effect of temperature should be considered at the higher peak currents and duty cycles. Eq. (1) also does not consider differing recombination mechanisms and trap filling, which results in a more complicated behavior.

Fabrication of Targets

Fabrication of the silicon targets was described previously.[1] The procedure for the GaAs targets (Fig 2) is now described. The targets were fabricated from semi-insulating wafers, 0.5 mm thick, with a resistivity of approximately 10^7 Ω-cm. The GaAs wafer was cut into device blanks using a low speed diamond saw. The blanks were chemically cleaned using hot TCE to remove wax, followed by successive one minute rinses in freon, acetone, and methanol. Blanks were etched in 1:3 HCL: H_2O for one minute, and cleaned in an ultrasonic cleaner for 10 minutes in deionized water.

Electrodes were formed by evaporating 400 angstroms of 88:12 Au:Ge alloy, followed by 5000 angstroms of gold, through moly masks onto the GaAs blanks. The masks were precision machined using an EDM machine. The gold-germanium alloy was used to insure good ohmic contact to the GaAs. The target electrodes were then alloyed at 450°C for 5 minutes in a nitrogen atmosphere. Gold wire leads were attached to the electrodes using a split tip welder. Targets were passivated by applying a silicon dioxide coating to the surface, followed by heat treatment. Recently samples have been passivated with silicon nitride in a nitrogen atmosphere. Contact resistance of the electrode was measured by observing the I-V characteristics during exposure of the semiconductor in the immediate vicinity of the electrode. Any barrier voltage present at the electrode is measured as an open circuit voltage.

Description of Laser

The laser diode array was made by Laser Diode Inc., Model LD 235. A total of 48 diodes make up the array, which emit at a wavelength of 0.904 microns. Measured dispersion was approximately 14° x 18°. The diodes were operated at a peak power output of 504 watts, as determined from the measurement of average power and optical pulse shape. The average power was measured with a TRG thermopile, model 101. Optical pulse shape was measured with an EGG photodiode, FND-100. Optical pulsewidth was varied by changing the length of the pulse forming line. Optical energy falling on the target was varied by either changing the distance between the laser and target, or by the use of neutral density filters. The diodes were switched with a mercury wetted switch or a krytron. The laser was operated at a PRF up to several hundred hertz.

Test Circuit

The test circuit is similar to the one employed previously[1]. Pulse bias of the semiconductor was used to avoid possible thermal runaway problems, particularly in the case of silicon. Energy storage was in the form of a 50Ω coaxial line. For measurement of recovery times, the pulse forming line was made long enough to insure measurement of the full recovery. Measurement of the pulse output was performed using high power, wide band attenuators and a 50Ω termination. The waveform was observed with a Tektronix 7834.

Experimental Results

Figures (3) and (4) show the variation of the gap resistance and recovery time of a silicon target as a function of the power, i.e., the energy falling on the target area normalized to the optical pulsewidth. The target gap is 1/2 mm and the width 1 mm wide. Measurements were obtained for optical pulses of 10 ns and 50 ns, with a pulse bias of 1 kV. As anticipated from Eq. (1) the gap resistance decreases with power level. Also, for the same power level, the gap resistance is lower for the longer optical pulse. The latter effect is also anticipated in view of the long recombination time compared to the optical pulsewidth. Under these conditions the resistance will decrease as the optical pulse is lengthened. Eq. (1) may be used as a starting point for predicting the experimental gap resistance in Fig. 3. Discrepencies (of order unity) are caused by previously mentioned factors: reflection, contact resistance, mobility changes, etc.

Note the significant result that at 15 W, equivalent to about 0.75 uJ, the resistance is approximately 18Ω. Only a small percentage of the total light falls on the immediate target area($\approx$ 3%), because of dispersion. Light falling outside the 1/2 mm X 1 mm area also

contributes to lowering the resistance, but to a much smaller degree. Lower gap resistances, perhaps as low as an ohm or so, appear within reach by concentrating the light onto the target area. This may be achieved by the use of fiber optics or precise focusing of the light by means of a lens.

In Fig. 4 the recovery time (50% point) is observed to increase with incident power and input energy. This effect may be caused by the filling of fast recovery traps, possibly located on or near the surface of the silicon. Such traps should be expected to have an important role when the depth of light penetration is small. Indeed, for the case of silicon, the penetration is only 20 microns or so, when using a .904 micron wavelength. As mentioned previously eq. (1) does not take into account trap filling; it assumes an infinite number of recombination sites.

In Fig. (5) a large silicon target is compared with a gallium arsenide one for the same light energy excitation and bias voltage (2kV). The two targets are identical in terms of gap length (5mm) and width (2mm). One should note the much larger gap resistance of the gallium arsenide sample. This is believed to be partly a result of the optical pulsewidth (50ns). Since the recovery of the gallium arsenide is shorter (approximately 10 to 20 ns) the gap resistance saturates early in the pulse while the resistance of the silicon target continues to decline. For shorter optical pulsewidths ($\approx$ 10ns) the gap resistances of the two materials are closer in value, although the gallium arsenide resistance still exceeds that of silicon. At .904 microns the photon energy is slightly smaller than the gap energy of GaAs, and this contributes to its larger resistance. Similar results were obtained when comparing Si and GaAs with 1 mm gaps

In Fig. (6) we compare two gallium arsenide targets having different gap lengths-one 5mm long and the other 3mm-as a function of bias voltage. The energy density falling on the effective target area is the same. From Eq. (1) the ratio of gap resistances (smaller target to the larger one) should be on the order of 3/5. This is in reasonable accord with the observations, keeping in mind the numerous factors which contribute to the gap resistance, but which have been omitted in Eq. (1). The observed increase in resistance beyond 1 kV may be caused by the reduction of the carrier mobility, which is dependent on field intensity.

Conclusions

Light activated semiconductors, both silicon and gallium arsenide, have been investigated using high power laser diode arrays as the light source. Gap resistances as low as 18Ω have been achieved in a 1/2mm x 1mm silicon target with a 500 W diode laser. Because of the large dispersion from the laser, only a small fraction of the light is actually utilized. A larger concentration of light may be achieved by using fiber optics or a lens. It would appear therefore, that by proper focusing of light onto the semiconductor, a bulk gap resistance on the order of an ohm or so is feasible. Comparison of silicon and gallium arsenide targets show that the gap resistance of the latter is larger, partly because of the diversion of light energy needed to make up for recombination effects, and partly because of the low photon energy compared to the gap energy of GaAs. At shorter optical pulsewidths (less than the recombination time of GaAs, or about 10ns) the resistances are more comparable. Recovery time in silicon targets was observed to increase with light energy, probably caused by trap filling.

One particular item not mentioned, but which is critical to the future success of the optical switch, is the driver for the laser diode array. At present the optical switch is limited by the slowness of the driver, which adversely affects the risetime and PRF capability. Several promising solid state candidates for the driver include MOSFETS, avalanche transisters, and snap-off diodes.

References

1. M. Weiner, J. Carter, R. Youmans, T. Burke, "Optically Activated Switch For Nanosecond Pulsers", Record of 15th Pulse Power Modulator Symposium. pp 164-167, June, 1982.

2. G. Mourou, W. Knox, "High Power Switching With Picosecond Precision", Appl. Phys. Lett, Vol 35 (7), pp. 492-495, Oct, 1979.

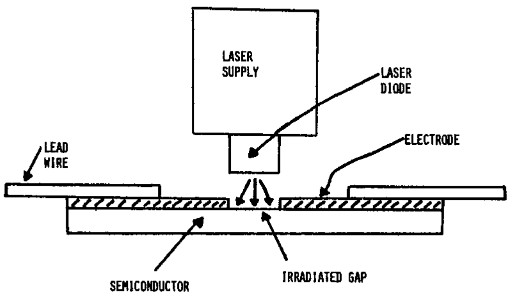

Figure 1: Optically Activated Semiconductor Switch.

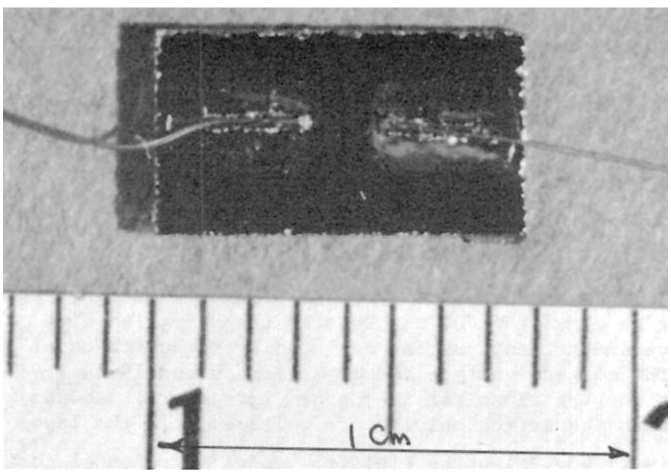

Figure 2: GaAs Optically Activated Semi-conductor.

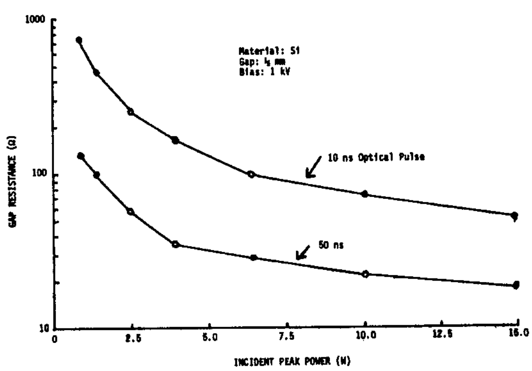

Figure 3: Gap Resistance as a function of incident power for 10 ns and 50 ns optical pulses.

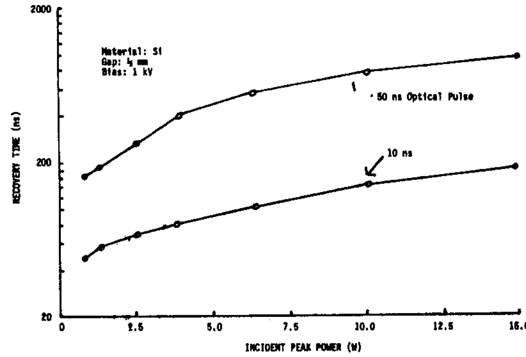

Figure 4: Recovery time as a function of incident power for 10 ns and 50 ns optical pulses.

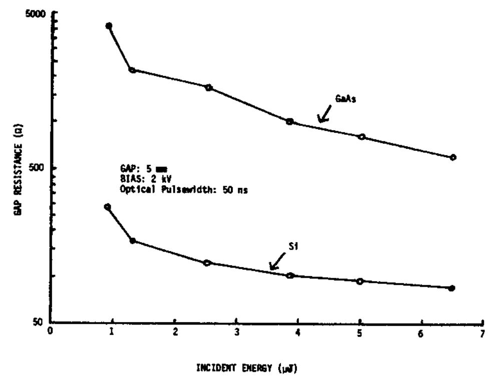

Figure 5: Comparison of gap resistance for Si and GaAs targets.

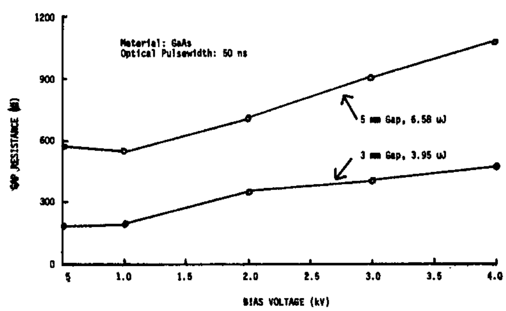

Figure 6: Gap resistance of GaAs targets with differing gap lengths.